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Plasma-wall self-organization in magnetic fusion

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Through a series of email exchanges, Thomas Klinger and Heinrich Laqua provided me with useful unpublished information about W7-X plasma breakdown

The L-mode density limit depends on the total input power *P (1)*

[A.Huber et al, J. Nucl. Mater. **438** (2013) S139] studies density limits in JET divertor experiments

Its abstract states: "*In contrary to the well known ‘heating power independent Greenwald limit’, the L-mode densities limit increases moderately with rising heating power (~$P^{0.4}$) independently on the wall material.*"

The L-mode density limit depends on the total input power *P (2)*

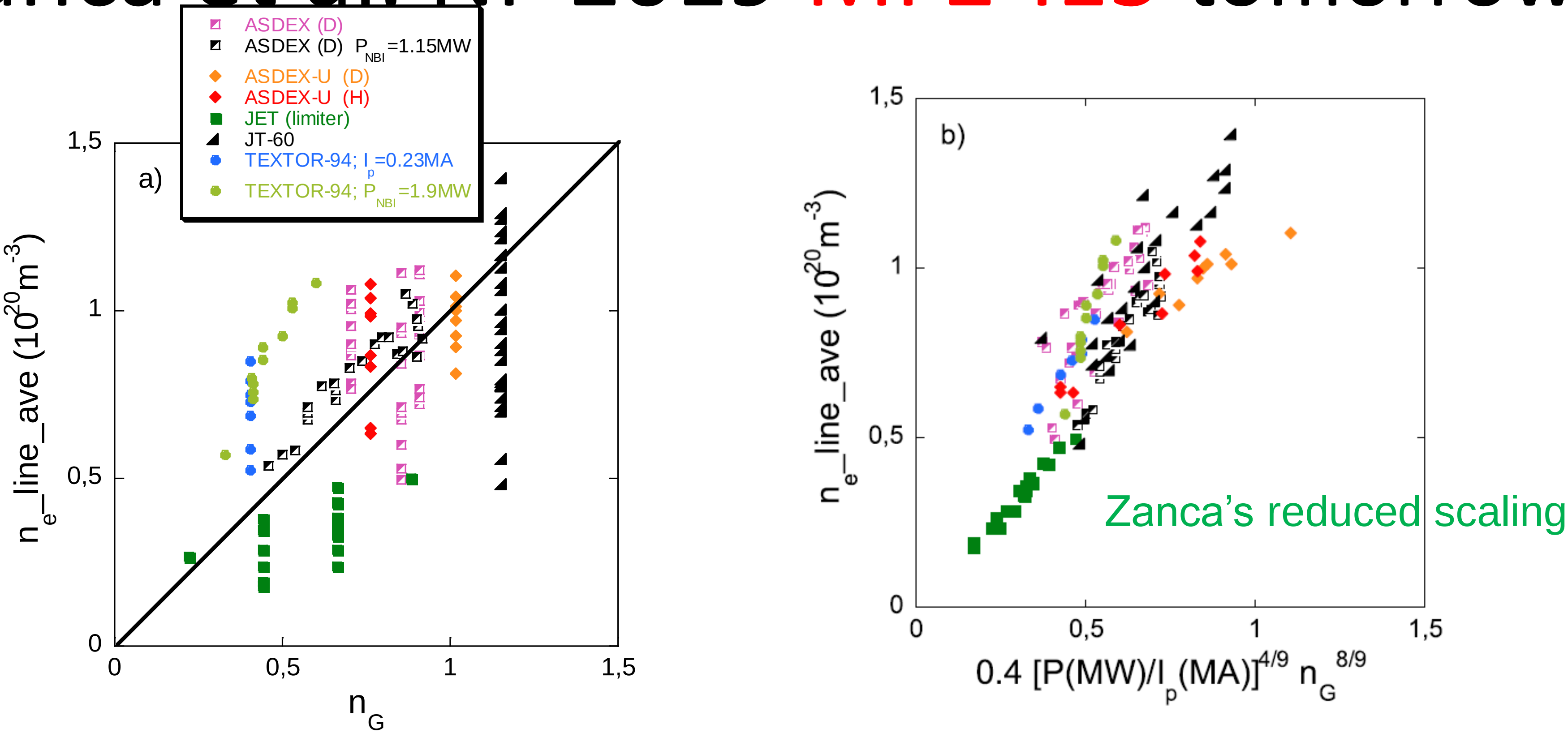
- Five papers published between 1986 and 1999 exhibit a clear scaling in *P*:

$P^{0.25-0.56}$ in ASDEX [1]
$P^{0.24 \div 0.33}$ in ASDEX-U [2]
$P^{0.44}$ in TEXTOR-94 [3]
$P^{0.47}$ in JET limiter [4];
$P^{0.5}$ in JT-60 [5]

[1] A. Stabler et al, Nucl. Fusion **32** (1992) 1557
[2] V. Mertens *et al*, *Nucl. Fusion* **37** (1997) 1607
[3] J. Rapp et al, Nucl. Fusion **39** (1999) 765
[4] G. Duesing and the JET Team, PPCF 1986
[5] Y. Kamada *et al*, *Nucl. Fusion* **31** (1991) 1827

The L-mode density limit depends on the total input power *P (3)*

Zanca et al. NF 2019 MF2-I15 tomorrow



Full Zanca's scaling has a factor > 1 depending on Z_{eff} and on n_0 the neutral density

Dropped here because the values of Z_{eff} and n_0 are not available in the papers providing the above data

The density limit: a radiative limit

The $[(P/I)^{4/9} n_G^{8/9}] \sim (IP)^{4/9}$ scaling is one of those in [Zanca et al., NF 2017 and 2019, and invited talk EPS 2021)]

Power-balance model using 1D single-fluid heat transport + on-axis Ohm's law with Spitzer resistivity

Excellent agreement with a broad experimental data base for the L-mode tokamak, the reversed field pinch and the stellarator [Fuchert et al. 2017, 2018]

This agreement supports radiation as the dominant element of this limit

This is why it includes a clear explicit dependency on P

A large part of it comes from impurity radiation

Plasma-wall self-organization

Aim #1 of this talk: introducing the concept of plasma-wall self-organization (PWSO) by simple zero and one-dimensional models

Basic idea of the theory : existence of a time delay in the feedback loop relating radiation and impurity production on divertor plates

Yields a delay equation whose simplest expression is $R_+ = \alpha(P-R)$, with P the total input power in the plasma, R the total radiated power, and R_+ its delayed value

Its fixed point $R= R_+$ corresponds to the plasma-wall equilibrium

Obtained by both a 0D and a 1D model

Plasma-wall self-organization

Yields a delay equation whose simplest expression is $R+ = \alpha(P-R)$, with P the total input power, R the total radiated power, and R+ its delayed value

The plasma-wall system is unstable for $\alpha>1$

Below detachment, α is proportional to the density

==> this threshold defines a density limit

which can be reached for a ratio of total radiated power to total input power as low as ½ for $R+ = \alpha(P-R)$

α has a factor corresponding to the amount of sputtered atoms on the plates of a divertor due to an impinging ion

The calculation works for the stellarator and the reversed field pinch too

Density limit and density freedom

When detachment develops, the plasma temperature at the plates decreases, which makes α to vanish, since sputtering does too

This pushes the radiative density limit to very high values when physical sputtering dominates radiation

There are two basins of PWSO at flat top:

- the usual one with a density limit
- a new one with density freedom, in particular for machines using high-Z materials

Self-organization during start-up

- After a particle confinement time is there a total loss of memory of the start-up? No!
- The impurity production during start-up determines an initial density limit
- If this limit is on the low side:
  - there is no screening of the wall by neutrals and a high temperature favorable to sputtering
  - At the end of start-up, no plasma detachment from the walls can occur, even no help to decrease the heat and particle loads leading to sputtering
- A high level of impurities is maintained leading to the usual density limit at flat top

Self-organization during start-up

- Operation is trapped into a bad basin of plasma-wall self-organization: usual one in ohmic start-up
- If the density at start-up is on the high side:

- There is a high density and a cold plasma till the formation of closed magnetic surfaces; low production of impurities
- Detached plasma when closed magnetic surfaces appear
- Flat top plasma in the density freedom basin

This would correspond to a good basin of plasma-wall self-organization

Aim #2 of this talk:

Experimental proposal for pushing the density limit to higher values

The basin with a high density limit might be reached by a proper tailoring of ECRH assisted ohmic start-up in present middle-size tokamaks, mimicking present stellarator start-up.

Already an important preliminary step: the passage to tungsten walls with the production of divertor detachment at high densities in JET [Huber et al 2013]

Basic idea…

- As yet, stellarators benefit from higher density limits than tokamaks
- This higher limit might not be intrinsic to the stellarator, but only to its mode of breakdown: the massive use of ECR power with high neutral density
- Starting from present (fortunately non acrobatic!) ECR assisted ohmic start-up scenarios, it might be possible to reach stellarator-like density limits in tokamaks by increasing progressively and simultaneously the ECR power and the initial neutral density
- Why not trying? It might be both interesting and useful!

Conclusion (1/4)

- The L-mode density limit is a radiative one
- The concept of plasma-wall self-organization is introduced by simple 0 and 1-dimensional models.
- Basic idea of the theory : existence of a time delay in the feedback loop relating radiation and impurity production on divertor plates
- The amount of radiation becomes unstable above a density limit
- It can be reached for a ratio of total radiated power to total input power as low as ½
- The calculation works for the stellarator and the reversed field pinch too

Conclusion (2/4)

- When detachment develops, the radiative density limit can be pushed to very high values when physical sputtering dominates radiation
- PWSO comes with two basins for this organization:

- the usual one with a density limit
- a new one with density freedom, in particular for machines using high-Z materials

Conclusion (3/4)

- Two basins of attraction of PWSO are shown to exist for the tokamak during start-up, with a high density one leading to density freedom during flat top

- A basin with a high density limit might be reached by a proper tailoring of ECRH assisted ohmic start-up in present middle-size tokamaks, mimicking present stellarator start-up and their lenient plasma-wall interaction

Conclusion (4/4)

- In view of the impressive tokamak DEMO wall load challenge, it is worth considering and checking this possibility, which comes with that of more margins for ITER and of smaller reactors
- By analogy with fluid dynamics, feathers, intelligent skin, supercavitation bubbles suggest there might be a new step in establishing peaceful relations between the walls of tokamaks and their thermonuclear plasma environment
- The start-up phase of tokamak discharges should get more attention: adults are strongly defined by genetics and education, also flat-top plasmas!